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Biochar

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Production and modifications of biochar to engineered materials and its application for environmental sustainability: a review

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Abstract

Biochar, a carbon-rich material produced from biomass waste through thermal conversion, holds great environmental promise. This article offers a comprehensive overview of the various feedstocks used in biochar production, the different types of thermal degradation processes, biochar characterization, properties, modifications to engineered materials, and their applications in the environment. The quality of biochar, including surface area, pore size and volume, and functional group formation, is significantly influenced by the specific conditions under which thermal conversion takes place. Each of the diverse processes employed to produce biochar yields a distinct set of properties in the final product. In recent years, biochar has gained widespread recognition and utilization in diverse fields such as wastewater treatment, carbon sequestration, reduction of greenhouse gas emissions, biogas production, catalysis in biofuel industries, construction, and soil enhancement. In summary, biochar is a promising environmental mitigation tool to achieve a sustainable environment. In addition to its benefits, the application of biochar presents several challenges, including the selection of feedstocks, methods of biochar production, modifications to biochar, the properties of biochar, and the specific applications of biochar. The current review summarizes factors that could lead to significant advancements in future applications.

Highlights

- The feedstocks and production of biochar were discussed.
- Activation of biochar and properties of biochar were narrated and summarized.
- Application of biochar for sustainable environment was discussed.

Keywords Biomass, Biochar, Thermal conversion, Pyrolysis, Engineered material, Environmental applications

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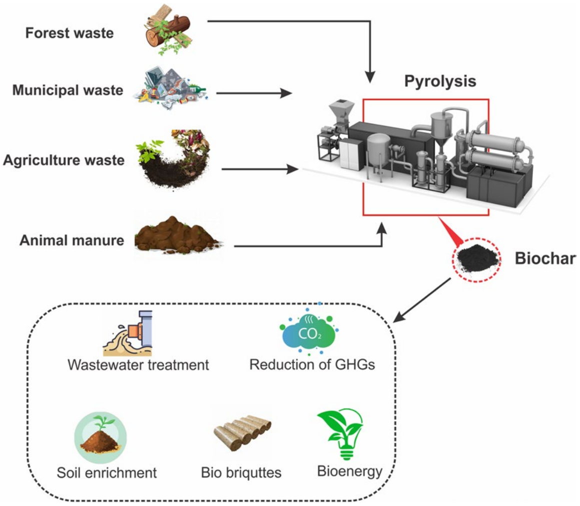
Graphical Abstract



1 Introduction

Rapid global development and population growth have led to pollution now recognized as one of the major challenges to the earth's ecology and living organisms (Briffa et al. 2020). The associated industrial processes lead to the emission of numerous hazardous substances such as dioxin, greenhouse gases (GHG), chlorofluorocarbon (CFC) gases, and $PM_{2.5}$ that are exceedingly difficult to clean up from the atmosphere (Manisalidis et al. 2020). Numerous techniques have been applied to remove these toxins from the environment; however, these are to a large extent not sufficiently efficient. Therefore, before reaching the environment, these contaminants need to be taken out of the point source to mitigate global warming and air pollution, hence new research is needed that focuses on finding affordable treatment strategies (Amjith and Bavanish 2022). Such techniques and strategies need to remove contaminants and allow for upcycling, such as biogas and bioenergy, the use of natural adsorbents and the manufacture of organic fertiliser as waste management options.

Sources of biomass waste including solid waste, animal waste, sewage sludge, industrial sludge, and forest waste are used for conversion into biochar, bio-oil, and syngas (Raud et al. 2019; Sadh et al. 2018; Kang et al. 2021). Biochar is one of the materials with a high carbon content that can naturally act as a carbon sink. The global interest in converting biomass into biochar and bioenergy is crucial to addressing climate change through reductions in GHGs (Oni et al. 2019). However, much of the biomass waste is still not properly disposed of, resulting in serious environmental consequences for the land, vegetation, and animals. According to the United Nations Environment Programme, over 140 billion metric tonnes of biomass waste are generated from crops worldwide each year. This paves the way for researchers to use biomass waste as a renewable energy source that can reduce the environmental impact. Population growth increases the demand for food crops, resulting in increased waste disposal into the environment. Indeed, the conversion of biomass into biochar and other value-added products is a rapidly growing field in waste management. This approach offers sustainable solutions for waste disposal, contributing to environmental preservation and resource utilization (Seow et al. 2022).

Biochar is referred to as a solid material formed by pyrolysis, carbonization, gasification, and torrefaction processes with high carbon content. Biochar is manufactured in a controlled atmosphere with no or limited oxygen. Biochar production has expanded due to the widespread availability of feedstock, biochar conversion technology and its uses in carbon capture, removal of organic toxins from wastewater, reduction of greenhouse gases, and the production of renewable energy (Uchimiya et al. 2011). Biochar's enhanced qualities are also regarded as an important mitigation tool in the agricultural sector. It provides several benefits, including enhanced soil fertility, lowered pH, higher water retaining capacity, increased humidity, and increased organic content. The biochar pH, physical–chemical properties including surface area and functional groups and capability to biosorb heavy metals are among its other characteristics. Biochar also acts as one of the important tools in climate change mitigation measures and sustainable engineering. Plants utilize CO_2 from the atmosphere through the process of photosynthesis, acting as a carbon sink. Biochar production from using plants as biomass will avoid the natural decay of the organic matter of biomass thereby reducing the emission of methane and nitrous oxide to the atmosphere. Additionally, the application of biochar to the soil will also result in the reduction of GHG emissions from the soil to the atmosphere. This proves that biochar will act as a sustainable method to address climate change. In this review, our exploration extends beyond conventional boundaries as we delve into the myriad conversion routes utilized to transform biomass into biochar. Furthermore, our focus extends to the activation processes and unique properties of biochar, unlocking the potential that renders it exceptionally versatile for application across diverse environmental contexts. This review not only synthesizes existing knowledge but also pioneers new insights, pushing the boundaries of biochar research and paving the way for innovative and sustainable solutions in environmental science and technology.

2 Feedstock for biochar production

The type of feedstock affects biochar production and quality. The feedstock utilized for biochar must possess low wetness and be rich in cellulose, lignin content and hemicellulose. The lower the moisture, the cheaper the drying and pre-treatment processes. Dry feedstock refers to feedstock with a moisture content of less than 30% while feedstock above 30% is referred to as wet feedstock (Jayaraju et al. 2021). Wet feedstock requires a pretreatment process incurring additional costs. Biomass can also be categorized as energy crops and biomass waste, with the first being purpose-grown crops that play a vital role in biorefining industries. Biomass from these energy crops is used for generating liquid fuels possessing low moisture content (< 10%), hence making the drying unnecessary (Jayaraju et al. 2021). Opposite to energy crops, biomass waste is produced from several sources. The mainstream of biomass waste comes from the agricultural sector, sewage sludge and solid, animal and food waste. The wastes classified as wet feedstock have a moisture content exceeding 30% and are divided into two categories: lignocellulosic and non-lignocellulosic. Lignocellulosic biomass, which includes agricultural and forest waste, energy crops, and wood biomass, offers certain advantages over non-lignocellulosic biomass like sewage sludge, algal biomass, and animal wastes when producing biochar. These advantages may include higher carbon content, lower levels of contaminants, and improved biochar properties for environmental applications. Due to the complex nature and diverse constituents of the feedstocks, non-lignocellulosic biomass creates a significant impact on critical management than lignocellulosic biomass (Krishnan et al. 2021; Farah Amalina et al. 2020). In addition, the presence of heavy metals and other toxic chemicals in biomass waste is a disadvantage during the production and handling of biochar as they pose hazardous effects to the environment while accumulating in human food webs. Non-lignocellulosic biomass has more harmful effects on the environment due to the presence of heteroatoms namely sulfur, phosphorus and nitrogen. It is also reported that some heavy metal ions are present in the non-lignocellulosic biomass in higher concentrations. It is essential to manage non-lignocellulosic biomass properly and implement effective waste management and pollution control measures to minimize the release of toxic metals into the environment (Senthil and Lee 2021). Figure 1 depicts the biochar conversion process, showcasing the various by-products. Value-added end products derived from biomass waste include biochar, syngas, ethane, methane, ethanol, and charcoal. Biochar serves a dual purpose as it is utilized as a soil nutrient and functions as an effective adsorbent.

Table 1 summarizes the lignin, hemicellulose and cellulose content of different biomass. It is seen that pine bark has a high lignin content of 38% followed by nut shells at 31%, whereas willow and softwood have a lignin content of 30%. Many researchers reported that pure lignin content will act as a substrate for biochar production and the quality of the biochar produced from lignin-rich biomass is always better than other feedstock.

3 Biochar production methods

Bio and thermochemical processes are utilized to turn biomass into a resource of renewable energy (Sadh et al. 2018). Full biomass disintegration is the primary benefit of the thermochemical processes as the biomass then transforms into charcoal, bio-oil or biogas. Biomass sources can also be degraded using biochemical procedures. The process of biochemical conversion including dark fermentation (anaerobic digestion) takes place with or without oxygen leading to the production of bio methane and carbon dioxide. Partial anaerobic digestion is performed when only 30–50% of the biomass waste is digested, but this method reflects several operational issues namely reduced biogas production, damages to process equipment, additional substrate requirements, poor mixing resulting in damages to metabolism, and nitrogen content resulting in the formation of metabolic by-products (ammonia, ammonium, nitrite, dinitrous oxide, and Nitrate) (Ambaye et al. 2020). Biomass waste is converted into organic compost during the aerobic digestion process under exposure to oxygen. Carbon dioxide, one of the greenhouse gases, emerged through aerobic

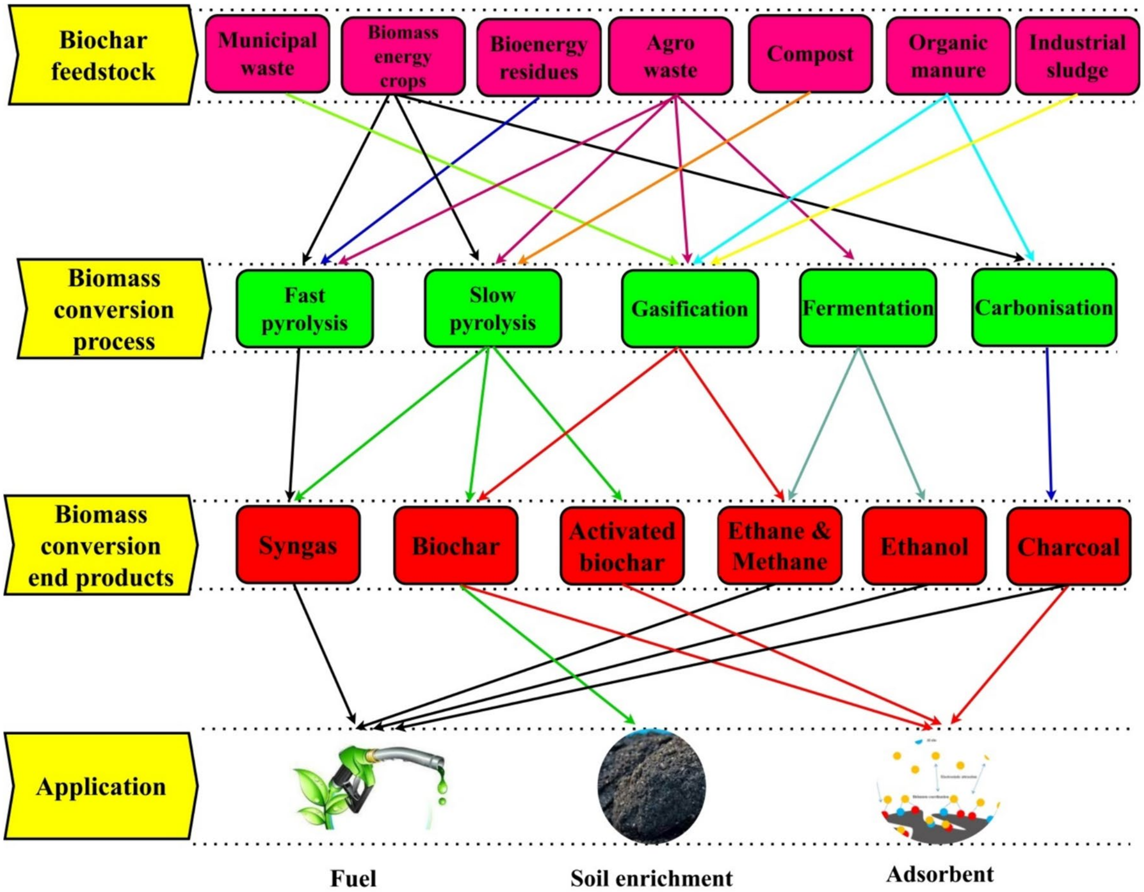


Fig. 1 The overall conversion process of biomass into biochar and its application

decomposition. Before this conversion, the cellulose and hemicellulose must be hydrolyzed into simpler substances (Chiappero et al. 2020). The hydrolysis process is carried out using hydrothermal energy, enzymes, and acids. Yeast is employed to convert sugar into ethanol or other important by-products. In the biochemical conversion technique, the lignin content of the feedstocks is not utilized completely and it will not oxidize completely (Alkurdi et al. 2019).

The lignin is completely degraded when applying thermochemical conversion technology (TCCT) processes including pyrolysis, gasification, torrefaction, and hydrothermal carbonization (Wang and Wang 2019). The combustion process is not considered a potential TCCT method for the production of biochar since it utilizes atmospheric oxygen and therefore creates an uncontrolled environment, resulting in the release of an enormous amount of heat at temperatures between 700 and 1200 °C leading to the production of ashes, carbon dioxide, and carbon monoxide. The gasification process is considered an alternate method to the combustion process since the gasification process utilizes a small amount of air resulting in partial degradation of the biomass. The partially degraded biomass will be utilized for the production of gaseous by-products at a temperature higher than 800 °C. Table 2 summarizes the diverse operating conditions of TCCT. Figure 2 illustrates the different methods available for biochar production using TCCT.

3.1 Pyrolysis methods

Pyrolysis is one of the promising techniques for the production of biochar. Biochar will be produced in the absence of oxygen or under a very limited supply of oxygen in the controlled environment at a temperature ranging from 300 to 700 °C. The end product is biochar, bio-oil and syngas (Senthil and Lee 2021). Biochar yield is maximum when the pyrolysis is performed with extended residence time. If the pyrolysis temperature is high with less residence time, it will result in the formation of bio-oil (Yaashikaa et al. 2019). So, the quality and properties of biochar depend on the type of pyrolysis process and its operating conditions. Biochar production using the pyrolysis process will happen in three-step mechanism namely char production, depolymerization,

Table 1 Lignin, hemicellulose and cellulose content of biomass (Anwar et al. 2014; Díez et al. 2020; Amalina et al. 2022a)

S. No	Feedstock/biomass	Lignin (wt. %)	Hemi cellulose (wt. %)	Cellulose (wt. %)	References
1	Bagasse	23.33	16.52	54.87	Guimarães et al. (2009)
2	Banana waste	14	14.8	13.2	Monsalve et al. (2006)
3	Corn cobs	15	35	45	Prasad et al. (2007)
4	Corn stover	19	26	38	Zhu et al. (2005)
5	Date Palm Rachis	12.49	40.40	33.08	Amalina et al. (2022a)
6	Fruit bunches	25.08	24.65	38.44	Amalina et al. (2022a)
7	Grasses	10–30	25–50	25–40	Malherbe and Cloete (2002)
8	Hard wood	20–25	20–25	45–50	Amalina et al. (2022a)
9	Hardwood	18–25	24–40	40–55	Malherbe and Cloete (2002)
10	Newspaper	18–30	25–40	40–55	Howard et al. (2004)
11	Nut shells	30–40	25–30	25–30	Howard et al. (2004)
12	Orange peel	12	49	54.1	Amalina et al. (2022a)
13	Pine bark	38	19	25	Hu et al. (2007)
14	Plum Pulp	3	41	45	Amalina et al. (2022a)
15	Poplar	24	50	26	Zhou et al. (2013)
16	Rice straw	10–15	20–30	25–35	Amalina et al. (2022a)
17	Rice straw	18	24	32.1	Prasad et al. (2007)
18	Soft Wood	27–30	20–25	35–40	Amalina et al. (2022a)
19	Softwood	25–35	25–35	45–50	Malherbe and Cloete 2002)
20	Sponge gourd fibres	15.46	17.44	66.59	Guimarães et al. (2009)
21	Spruce bark	26	42	27	Burhenne et al. (2013)
22	Sugar cane bagasse	20	25	42	Kim and Day (2011)
23	Sweet sorghum	21	27	45	Kim and Day (2011)
24	Wheat straw	16–21	26–32	29–35	McKendry (2002)
25	Wheat straw	16–21	26–32	30–35	Amalina et al. (2022a)
26	Wheat straw	15	38	29	Demirbaş (1997)
27	Willow	29.3	41.7	16.7	Wang et al. (2017)

Table 2 Operating conditions during different thermochemical conversion methods (Amalina et al. 2022a)

S. No.	Method	Temperature (°C)	Heating Rate (°C s^{-1})	Residence time	Syngas (%)	Bio-oil (%)	Biochar (%)	References
1	Slow pyrolysis	300 to 550	1–10	Several Hours	35	30	35	Shahbaz et al. (2022)
2	Fast pyrolysis	450 to 600	10–1000	10–30 s	13	75	12	Thomas et al. (2019)
3	Flash pyrolysis	750 to 1000	Less than 1	Less than 2 s	–	–	–	Thomas et al. (2019)
4	Gasification	More than 800	1–0.8	10–20 s	85	5	10	Zaied et al. (2020)
5	Microwave-assisted pyrolysis	400 to 800	1000 +	–	–	–	–	Zaker et al. (2019)
6	Hydrothermal carbonization	Less than 200	Less than 1	1 to 16 h	35	30	35	Brown et al. (2020)
7	Torrefaction	450 to 550	–	Less than 2 h	5	20	75	Amalina et al. (2022b)

and fragmentation (Rangabhashiyam and Balasubramanian 2019). The thermal degradation of the biomass during pyrolysis will result in the rearrangement of inter and intra-molecular structures resulting in the formation of benzene rings and aromatic polycyclic compounds (Karimi et al. 2018). Depolymerization is the dissolution of polymers, which leads to the formation of monomers, dimers, and trimers. Fragmentation occurs when polymer and monomer links degrade due to thermal degradation, resulting in the formation of gaseous products (Lam

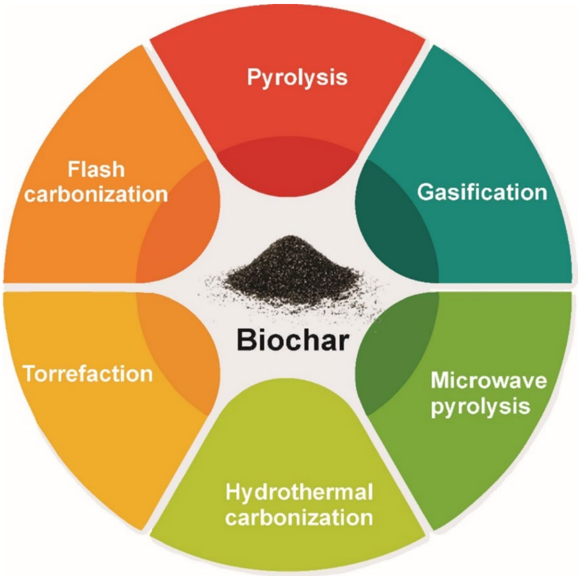


Fig. 2 Different methods of thermochemical conversion process

et al. 2019). However, the gas products are unstable, and secondary cracking would occur and result in the formation of volatile organic compounds (Yu et al. 2019) due to partially decomposed organic matter. This process is called recombination (Dhyani and Bhaskar 2018). The primary char produced initially will catalyze the production of secondary char. Three different types of pyrolysis exist: slow, rapid, and flash pyrolysis.

Slow pyrolysis is thought to be a desirable approach for producing biochar. It is performed at a low pyrolysis temperature (300 to 550 °C), slow heating rate (<0.8 °C s^{-1}), and extended residence time (average: 5 to 30 min and in some cases up to 35 h) (El-Naggar et al. 2019). Secondary char is produced with the residence time increasing, maximizing the biochar yield (Das et al. 2021). Aside from these operating conditions, the composition of the biomass utilized for biochar production has a significant effect on biochar yield. The mineral-rich biomass will result in low biochar yield because the minerals will cause more complex reactions simultaneously and in different orders during pyrolysis. This complex process will produce biochar of high ash content, affecting the overall biochar yield. Mineral-rich biomass differs from conventional biomass due to the presence of more silicates, inorganic compounds, and alkaline rare earth metals. Sewage sludge from wastewater treatment plants, food waste digestates from anaerobic digestion, and biomass grown with chemical fertilizers are the common mineral-rich feedstocks (Nair et al. 2022).

Intermediate pyrolysis operates in a temperature range of 450 to 550 °C and its pyrolysis temperature is higher than that of slow pyrolysis and lower than that of fast pyrolysis. Intermediate pyrolysis can avoid the development of higher molecular weight tars that favor the creation of fine biochar together with bio-oil and syngas production. The size and shape of biomass are not crucial factors in intermediate pyrolysis as compared to fast pyrolysis (Sakhiya et al. 2020). The yields of biochar, bio-oil, and syngas produced from different feedstocks are presented in Table 3. It is clear that in most of the thermochemical conversion technology, pyrolysis temperature varied from 400 to 550 °C. Pine bark and oil sludge resulted in a biochar yield of more than 50%, whereas pitch pine, red oak, and eucalyptus resulted in higher bio-oil production of more than 60%.

Fast pyrolysis temperature operates at a temperature near 1000 °C, with a short residence time (0.5 to 2 s) and a high heating rate (10 to 1000 °C s^{-1}) (Tomczyk et al. 2020). Fast pyrolysis produces increased bio-oil yield rather than biochar because of the rapid heat transfer rate and biochar chipping, which degrades the actual biomass's macroscopic structure in large quantities (Bruckman and Pumpanen 2019) Generally, better results were seen during fast pyrolysis when the feedstock was small, finely ground, and less than 3 mm in size (Kapoor 2021). Organic wastes and other biosolids can be effectively pyrolyzed when the moisture content is less than 10%. Higher moisture content also led to an increase in the production of unidentified gas products, which may indicate a higher conversion rate of organic liquids. Thus, the research challenge is to determine the optimal moisture content of a given feedstock for a given thermochemical processing technology (Eke et al. 2020). If the pyrolysis temperature is increased to 1000 °C, the end product obtained will be mostly biogas. Flash pyrolysis operates at a temperature higher than 1000 °C and a rapid heating rate of 1000 °C s^{-1} with a shorter residence time of less than 0.5 s (Li et al. 2013). The end product of flash pyrolysis was reported to show a higher yield of bio-oil (60–80%), a low yield of syngas (10–20%), and a biochar yield of 10–15%. Fast pyrolysis results in 30–60% of bio-oil, 15–35% of syngas, and 10–15% of biochar respectively.

3.2 Microwave assisted pyrolysis

Microwave-assisted pyrolysis (MAP) is a novel addition to the TCCT process. Microwaves are well-known for converting homogeneous waste into energy feedstocks (Ge et al. 2021). The advantages of MAP over the other pyrolysis processes are a fast heating rate, high bio-oil and syngas yield, improved energy efficiency, uniform heating rate, low energy loss and high energy conservation rate. Another important advantage of the microwave process is a biomass with high moisture content dissociates at higher temperatures (Pfaltzgraff and Clark 2014).

Table 3 Yield of biochar, bio-oil, and syngas using different feedstocks (Sakhiya et al. 2020)

S. No.	Feedstock	Temperature (°C)	Biochar (%)	Bio-Oil (%)	Syngas (%)	References
1	Camphorwood Sawdust	500	26–30	51–62	12–19	Fan et al. (2015)
2	Douglas fir, Red Oak	500	22–24	66–67	8	Le Brech et al. (2016)
3	Eucalyptus	500	14–26	60.3	–	Joubert et al. (2015)
4	Wheat straw, Wheat bran, Softwood, hardwood	500	15–24	51–69	16–24	Henrich et al. (2016)
5	Oil Sludge	480	54–86	8–22	2–29	Ma et al. (2014)
6	Olive Stones	500	26	38	35	Sanginés et al. (2015)
7	Palm Oil decanter	500	39	41	20	Dewayanto et al. (2014)
8	Pine Chips	500	28–31	45–54	18–27	Westerhof et al. (2012a)
9	Pinewood chips	500	30	58	12	Liaw et al. (2013)
10	Pinewood Sawdust	450	19	54	–	Wang et al. (2011)
11	Oak	450	18–20	49–56	–	Ingram et al. (2008)
12	Pitch Pine	500	13–16	64–66	21–22	Kim et al. (2013)
13	Rice Husk	500	26–38	47–54	13–20	Fukuda (2015)
14	Rice Straw, Corn Con, Sugarcane bagasse	500	20–31	53–67	15–17	Phan et al. (2014)
15	Sugarcane bagasse	530	26	51	22	Westerhof et al. (2012b)
16	Switch Grass	510	19	60	16	Greenhalf et al. (2013)

The pyrolysis process in microwaves involves the transfer of energy within the biomass rather than transferring through its surface (Liu et al. 2021b). It also uses electromagnetic energy instead of thermal energy. In traditional pyrolysis, heat is transported from the biomass' exterior to its interior. Many functional groups will be broken down as a result of this degradation. But microwave heating will happen from the central core to the surface of the biomass. This will expand the surface area of the biochar produced, form more pores, and result in the formation of many functional groups (Naji and Tye 2022). MAP will also result in the formation of a stable pore structure in the biochar due to a decrease in the hydrogen-to-carbon (H/C) ratio. As the reaction temperature increases in the MAP, it results in a decrease in hydrogen and oxygen content due to the cleavage of the weak bonds, and further, it increases the carbon content of the biochar (Zhang et al. 2022b). The specific surface area and pore volume of the biochar always increase with the increase in reaction temperature. As the temperature increases during MAP, more gaseous products are formed, and these gaseous products will result in the expansion of the biochar pores (Zhang et al. 2022b). Table 4 summarises the yield of biochar, bio-oil, and syngas using the MAP process. From Table 4, it is clear that any type of feedstock (dry and wet biomass) can be used for biochar production in the MAP process. Sewage sludge has more moisture content and 63% is yielded as syngas and the yield of biochar is 13% using the MAP process. Waste cooking oil resulted in 67% of bio-oil and only 13% of biochar yield. It is also observed that sawdust resulted in 61% of the biochar and a very low syngas yield of 8.6%.

3.3 Other methods

3.3.1 Torrefaction

Torrefaction is a process that uses a moderate temperature ranging from 300 to 550 °C at a heating rate of 50 °C min^{-1}, and a moderate residence time of 20 to 40 min to transform biomass into biochar and other products namely bio-oil and syngas (Manyà et al. 2020). In this process, the moisture content of the biomass is removed and other components namely lignin, cellulose and hemicellulose are partially degraded. In addition, the torrefaction process will produce biochar as a solid product rather than liquid or gaseous by-products. The biochar produced in this process will have very good quality namely high energy density, hydrophobicity, and low oxygen-to-carbon ratio. High-quality biochar will always have a very low oxygen-to-carbon (O/C) ratio, which should be between 0.2 to 0.6 and preferably 0.4 (Daful et al. 2020). The carbon stability of the biochar depends on the O/C ratio since a higher O/C ratio will result in increased oxidation of substrate and will reduce loss of carbon in the form of carbon dioxide. Similarly lower level of O/C ratio will increase the stability of the biochar and if the O/C ratio is less than 2, the biochar half-life period will increase to 1000 years. However, the biochar produced from the torrefaction process will have an O/C

Table 4 The yield of biochar, bio-oil, and syngas in MAP using different feedstocks (Sakhiya et al. 2020)

S. No.	Feedstock	Temperature (°C)	Biochar (%)	Bio-oil (%)	Syngas (%)	References
1	Corn stover, aspen wood	450–550	25–31	35–42	–	Wan et al. (2009)
2	Corn straw bale	200–600	34	32.5	29	Zhao et al. (2011)
3	Douglas fir sawdust	300–500	31–61	31.4–53.9	7.9–15	Ren et al. (2012)
4	Maize stalk	500	15.2–30.5	22.6–69.9	15–19	Zhang et al. (2016)
5	Peanut shell	300–600	31.25–37.2	13.56–22.01	40.22–51.85	Miura et al. (2004)
6	Pine sawdust	300–600	20.2–35.27	20–33.18	42.48–59.8	Mamaeva et al. (2016)
7	Sewage sludge	1000	10–13	2.2–4	16–27	Menéndez et al. (2007)
8	Sugar cane, corn stover, rice straw	489–595	18–22	42–46	32–40	Huang et al. (2016)
9	Waste oil	250–700	5–13	67–72	15–28	Lam et al. (2012)
10	Wheat straw	400	46.5–56	25–30.5	17.5–21	Zhao et al. (2012)
11	Wood blocks	110–260	18.249.7	–	–	Miura et al. (2004)

ratio greater than 0.4 resulting in poor quality of biochar. Therefore, the torrefaction process is considered a pre-processing treatment method to reduce the moisture content, thereby increasing the heating rate of the biomass. Torrefaction's biochar yield will be between 30% and 70% (Enaime et al. 2020).

3.3.2 Hydrothermal carbonization (HTC)

HTC is used to produce hydrochar from biomass waste, whereas typical biochar is produced from the pyrolysis process. The properties of biochar and hydrochar will vary since biochar is produced in the dry carbonization process and hydrochar is produced in a phase mixture of solid and liquid (Kambo and Dutta 2015). HTC is considered one of the promising technologies for the conversion of waste to energy since the energy associated with the pre-treatment of the wet biomass is very low. HTC involves a three-step process namely dehydration, decarboxylation, and decarboxylation for which pre-treatment of feedstocks is not required. Biomass with a moisture content of 75 to 90% also can be converted into hydrochar, bio-oil, and syngas using HTC technology (Kumar and Ankaram 2019). The hydro char produced by the HTC technology can be used as a fuel and can be considered as an alternate source for coal. Hydro char also can be used as a feedstock for a gasification process, acts as an adsorbent in the waste and water treatment and used as an additive for soil enrichment (Kumar and Ankaram 2019).

3.3.3 Gasification

Gasification is a process that uses oxygen, atmospheric air, and steam at a temperature of more than 750 °C to create biochar, bio-oil and syngas using the heat generated from biomass waste during thermal degradation. When air is used as the gasification agent, more syngas, including hydrogen, carbon dioxide, methane, nitrogen, and acetylene, will form. When steam is used as a gasification agent with a huge heating value, hydrogen production will be at its highest (Nidheesh et al. 2021). Four steps are involved in the gasification process: drying in the first step, pyrolysis in the second, oxidation in the third, and reduction in the fourth (Umenweke et al. 2022). If gasification is carried out using the contact bed and inlet flow method, syngas is produced in greater quantities than biochar. One of the main disadvantages of gasification is controlling temperature since it uses air and oxygen. When compared to other conversion technologies, the gasification process emits more greenhouse gases and the yield of biochar is significantly less when compared to syngas. The syngas produced from the gasification process is composed of hydrogen, carbon dioxide, methane and nitrogen. When air is used as the gasifying agent, around 56 to 59% (Vol.%) is produced as nitrogen. When oxygen and steam are used as a gasifying agent, hydrogen gas is produced in 30 to 34% (Vol.%) and 24 to 50% (Vol.%), respectively (Makwana et al. 2023). So, gasification is deemed as a suitable technology for the production of syngas and hence not recommended for the production of biochar. Table 5 summarizes the advantages and disadvantages and other operating conditions of different thermochemical conversion technologies of waste biomass.

4 Properties of biochar

The duration of residence, heating rate, and pyrolysis temperature are the key operating conditions that demonstrate the biochar's features and attributes. As discussed in the torrefaction section above, biomass waste that is high in carbon content and low in oxygen content will produce a high yield of biochar when compared to biomass with very low carbon content and high oxygen

Table 5 Comparison of different thermochemical conversion technologies for biochar production (Zhao et al. 2017b; Walling et al. 2019)

Thermochemical conversion technology	Need	Atmosphere	Reaction medium	Gas released	Advantage	Disadvantage
Combustion	Waste biomass to heat	Oxidizing atmosphere	Air	CO_2 and H_2O	• Acts as a Fuel Source • Relatively simple Process	• NOx, SOx, and particulates are formed during combustion • Other potential unburnt pollutants, such as CO, PAHs, condensed fumes (tars/oils), soot, and unburnt carbon also have negative environmental implications
Pyrolysis	Waste biomass to biochar and bio-oil	No oxidizing atmosphere	None	CO, H_2, CH_4 and other hydrocarbons	• Established technology and infrastructure • Feedstock quality is not essential • Up to 90% reduction of volume	• Air pollution and GHG emissions • Flue gas cleaning • Low energy efficiency
Microwave Assisted Pyrolysis	Waste biomass to bio-oil	Microwave heating		H_2, CH_4, CO, and CO_2	• Fast and homogeneous internal heating • improved energy efficiency Low energy loss • High energy conversion rate	• Non-uniform heating • Uneven reaction temperature • Product inconsistency • Difficulty of large-scale production
Torrefaction	Waste biomass to bio-oil and bio-solids	Inert atmosphere	inert atmosphere, flue gas, hydrothermal media, or hot compressed water	CO_2, CO, and e CH_4	• Reduced emissions • Syngas, biofuels, and biochar production • Up to 90% reduction in volume • Zero waste process	• Feedstock sensitivity • Extensive gas cleaning of the syngas • High investment costs
Hydrothermal carbonization	Waste biomass to hydro char, bio-oil and biogas	Subcritical water	Water	CO_2	• Can treat wet waste • Reduces waste volume • Produces energy-dense hydrochar • Produces carbon fuel	• High capital costs • High energy consumption • Excessive water use • Limited feedstock options
Gasification	Waste biomass to producer gas	Partial oxidizing atmosphere	Air, pure oxygen, steam, and CO_2	CO, H_2, CO_2, H_2O, and CH_4	• High efficiency of energy recovery • Reduced emissions • Syngas and biochar production	• Complex technology • Extensive gas cleaning of the syngas • High investment and operating costs

content. High oxygen content of biomass will result in oxidation of the substrate and carbon is lost in the form of carbon dioxide thereby reducing biochar yield. For instance, the yield of the biochar produced from organic manure is very low when compared to the yield of the biochar produced from wood biomass or any other crop residues. Organic manure will create very little biochar since it contains very little carbon, whereas a slightly high pH in the biomass may encourage the production of ash content. Organic manure is composed of many organic and inorganic compounds and these compounds during the pyrolysis process will result in the formation of more ash content. The ash contains more minerals and can be used as compost for organic gardening.

Due to the presence of higher amounts of lignin, hemicellulose, and cellulose, lignocellulosic feedstocks-based biochar has high carbon content. The lignin content of a biomass is composed of several functional groups with aromatic substructure and lignin is a hydrophobic polymer and amorphous with very high molecular weight. During thermal degradation, lignin is more stable when compared to cellulose and hemicellulose since cellulose and hemicellulose are made up of simple sugar monomers that can be easily degraded at 450 °C (Tomczyk et al. 2020). So, the higher lignin content of the biomass promotes more carbon content in. the biochar. Therefore the properties and yield of biochar depend on the type of feedstocks used for the biochar production. In this part, the characteristics of biochar were thoroughly reviewed and Tables 5 and 6 summarize the different properties and elemental composition of biochar.

4.1 Physical properties

Physical properties include specific surface area, particle size, pore size, pore volume, and density of the biochar (Campos et al. 2020). The properties of the biochar are outlined in Fig. 3 and pyrolysis temperature has a significant impact on the biochar's physical properties. During pyrolysis, the moisture and volatile organic content of the biomass results in the development of pores on the biochar surface due to expulsion (Yuan et al. 2015). An increase in pyrolysis temperature will result in an increased release of volatile organic matter and creates more pores and also an increase in pyrolysis temperature increases syngas production. Also, it creates more pores in the biochar. A pore size greater than 50 nm is called a macropore, a pore size between 2 and 50 nm is called a mesopore, and a pore size less than 2 nm is called a micropore (Saleh 2022). These pores developed on the surface of the biochar are thought to be one of the crucial physical characteristics that can lead to the maximum solubilization of toxic pollutants during the adsorption process, catalytic activity, and soil bioremediation (Greenough et al. 2021).

Table 6 Properties of biochar derived from the different feedstock (Amalina et al. 2022a)

S. No.	Feedstock	Method	Surface area ($m^2\ g^{-1}$)	Residence time	Temperature (°C)	pH	Volume ($cm^3\ g^{-1}$)	References
1	Corn stover	Microwave assisted pyrolysis	43.4	15 min	650	10.5	–	Nidheesh et al. (2021)
2	Manure	Slow pyrolysis	13	4 h	500	10.5	–	Song et al. (2019)
3	Paper industry sludge	Slow pyrolysis	47.42	2 h	500	8.78	0.063	Lu et al. (2020)
4	Peanut shell	Slow pyrolysis	448.2	3 h	700	10.57	0.2	Thomas et al. (2019)
5	Pine saw dust	Fast pyrolysis	6.2	3 s	400	4.2	0.011	Lee et al. (2020)
6	Pine wood	Slow pyrolysis	380	0.5 h	500	8.7	0.15	Leng et al. (2021)
7	Pine wood	Fast pyrolysis	4.8	2 s	400	–	–	Leng et al. (2021)
8	Pine wood	Microwave assisted pyrolysis	52.1	15 min	650	7.85	–	Nidheesh et al. (2021)
9	Rice husk	Slow pyrolysis	230.91	2 h	500	7.99	–	Kameyama et al. (2019)
10	Rice straw	Slow pyrolysis	156.2	3 h	600	9.7	0.084	Alkurdi et al. (2019)
11	Sludge	Microwave assisted pyrolysis	110.8	10 min	700	–	0.07	Zaker et al. (2019)
12	Straw pellet	Microwave assisted pyrolysis	1.14	–	200	–	0.37	Ge et al. (2021)
13	Switch grass	Fast pyrolysis	2.1	30 s	600	10.6	0.023	Oliveira et al. (2017)
14	Wheat straw	Slow pyrolysis	183.3	3 h	600	9.1	0.091	Alkurdi et al. (2019)
15	Wood bark	Slow pyrolysis	350	0.5 h	500	9.8	0.14	Dhyani and Bhaskar (2018)

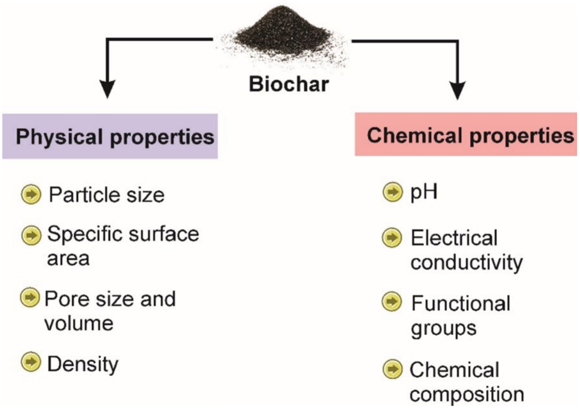


Fig. 3 Properties of engineered biochar

The formation of micropores and mesopores during pyrolysis plays a very important role in the adsorption process. During the sorption process, the pores present in the biochar will act as adsorption sites and the adsorbates will bind to these sites increasing the sorption capacity of the biochar. Application of porous biochar to the soil will also result in the sorption of heavy metals (electrostatic attraction and precipitation) and other pollutants (surface adsorption and partition). Similarly, carbonaceous biochar, due to its heterogeneous nature, acts as a green catalyst in many biorefinery industries due to its enhanced characteristics namely stable pore structure, presence of several functional groups and larger surface area. Several other physical and chemical techniques activate or modify the biochar's properties to further improve the physicochemical properties of the biochar. One of the crucial physical characteristics that can improve the effectiveness of biochar in environmental applications is the pore volume and particle size. For instance, biochar particle size is very important in soil water storage capacity. Intrapores (pores inside particles) and interpores (pores between biochar and soil) play a major role when biochar is applied to the soil. Biochar particles will have different pore sizes and shapes, and they will mix with the soil resulting in changes in the interpores characteristics and affecting water storage capacity when it is applied to soil (Liu et al. 2017).

Mechanical stability, rigidity, and feedstock composition are essential variables in biochar production that significantly influence the final properties of biochar, including porosity, density, and particle size. Porosity has an inverse relationship with mechanical stability and is directly proportional to density. If the particle density of biochar is higher, it indicates the presence of more micropores since the diameter of the micropores is less than 2 nm, and during the pyrolysis process, if more mesopores are formed (diameters 2–10 nm), the particle density of the biochar will be less (Weber and Quicker 2018). Table 6 summarizes the physical characteristics of the biochar at various temperatures for diverse feedstocks.

4.2 Chemical properties

Understanding the chemical properties of biochar is crucial for tailoring its properties to specific applications. For instance, modifying the feedstock or pyrolysis conditions can be employed to enhance biochar's adsorption capacity, alter its nutrient release patterns, or improve its suitability for specific soil types. Additionally, the chemical properties play a significant role in determining the environmental impact of biochar application, especially when used to remediate contaminated soils or water bodies. The elemental composition of the various feedstocks is summarized in Table 7. Biochar's chemical characteristics are greatly influenced by the presence of carbon, oxygen, nitrogen, and hydrogen in biomass. During the pyrolysis process, chemical modifications result in the formation of several functional groups and enhance the chemical characteristics of the biochar. (Rodriguez Ortiz et al. 2020). The hydrogen and oxygen content of the biomass reduces during the pyrolysis process and the carbon content of the biomass is converted into hydroxyl and aromatic carbon bonds. Additionally, as the pyrolysis process involves raising the temperature, several changes occur. The volatile organic content of the biomass undergoes degradation, leading to the release of gases. Hydrogen bonds present in the biomass are also decomposed during this process and also increase pH. The increase in pH is due to several reasons namely the increase in ash content at elevated pyrolysis temperature, the increase in calcium and magnesium carbonates, and acidic functional groups' losing their oxygen at elevated temperatures thereby increasing the pH. Furthermore, the elevated temperature causes an increase in the formation of free radicals within the biochar. The degradation will typically take place in three different zones and it is evaluated using thermogravimetric analysis. The biomass' moisture content was primarily eliminated during the first decomposition (Teutscherova et al. 2017). The biomass' lignin, hemicellulose, and cellulose are partially and fully degraded during steps 2 and 3, respectively. The chemical properties of the biochar depend on the pyrolysis temperature and the higher the pyrolysis temperature, the lower the biochar yield.

Table 7 Elemental composition of different feedstocks (Zhou et al. 2021; Amalina et al. 2022a)

Feedstock	Ash (%)	C (%)	H (%)	N (%)	O (%)	References
Beef manure	18.05	41.85	4.9	32.36	32.36	Zhou et al. (2018b)
Cattle manure	34.88	30.96	2.34	2.67	63.62	He et al. (2021)
Chicken manure	37.14	30.89	4.39	2.28	24.77	Zhou et al. (2018a)
Corn cob	4.25	44.1	7.98	0.7	46.75	He et al. (2021)
Cow manure	23.44	67.28	6.22	3.36	23.14	Lin et al. (2021)
Dairy cattle manure	24.6	38.5	5	3.4	42.4	Jung et al. (2021)
Date palm leaf	11.58	43.14	7.49	0.2	52.7	Badawi et al. (2022)
Date palm Rachis	5.5	39.95	7.19	0.16	52.70	Hassan and Carr (2021)
Date Pam Gleich	2.4	43.65	7.59	0.16	52.74	Amalina Ishak et al. (2019)
Food waste	10.3	47.5	3.9	31.3	6.6	Lee et al. (2021)
Fruit Bunch	4.2	43.49	7.51	0.19	52.73	Amalina Ishak et al. (2019)
Goat manure	16.77	42.08	5.62	1.45	39.85	Erdogdu et al. (2019)
Hard Wood	9.86	53.96	1.83	1.24	42.98	Ayaz et al. (2021)
Plum Pulp	–	39.32	4.75	2.40	53.3	Contescu et al. (2018)
Rice husk	17.1	37.8	5.5	0.3	39.3	Fleig et al. (2021)
Rice Straw	–	34.24	3.31	1.5	37.6	Daffalla et al. (2020)
Sargassum	43.43	28.5	2.78	2.13	21.97	Niu et al. (2021)
Soft Wood	58.53	22.67	1.31	3.04	72.99	Singh and Chandra (2019)
Spirulina	7.16	44.16	6.97	10.69	29.86	Niu et al. (2021)
Swine manure	21.33	51.18	6.82	3.01	16.82	Zhou et al. (2018a)
Wheat Straw	3.6	70.6	3.5	4.46	15.8	Qayyum et al. (2020)

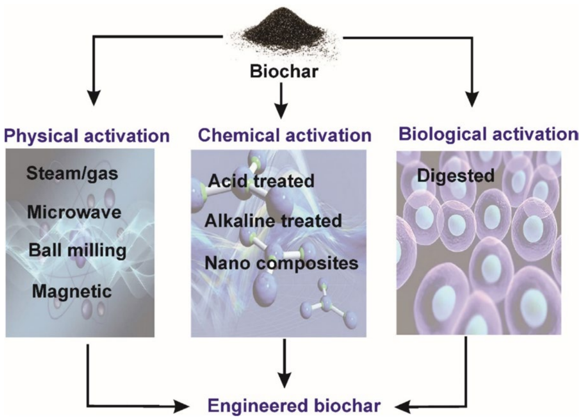


Fig. 4 Different activation/modification methods of biochar

5 Biochar modifications

In recent years, many agricultural processes and industries have converted biomass waste into biochar to diminish the volume of waste disposed into the environment. The produced biochar is finding wide application in soil enrichment, wastewater treatment, and several other applications. The activation of biochar is done to improve its physicochemical characteristics. Biochar can be activated by physical, chemical, or biological methods, respectively. Figure 4 illustrates the different activating agents used to modify the characteristics of biochar. When compared to biological procedures, physical and chemical methods have several advantages. The biological activation phase entails the digestion of the biochar, which will increase the microbial population of the material and increase the soil's nutritional content.

5.1 Physical modifications

A material's porosity is increased using a physical method in an oxidative or oxygen-rich environment. The most popular physical activation techniques are the utilization of steam, gas, ball milling, magnetic properties, and microwave-assisted activation (Banerjee et al. 2016). The surface area and pore size of the biochar are improved using the steam created during heating. To promote pore formation, the produced biochar is heated between 700 and 900 °C. The formation of micropores rather than mesoporous structures will increase with further physical activation. The temperature, activating substance, and level of activation all contribute to the success of physical activation. The porous nature of the biochar increases with the rise in temperature and air is considered one of the most successful activating agents since it requires a very little amount of energy and is cost-effective (Cárdenas-Aguiar et al. 2017). Air oxidation is well known for its several advantages namely easy access to air, and chemicals are not used, resulting in very less wastewater generation. But the main drawback of air is that it can cause pyrolysis to switch to a combustion process, where more heat is released and less biochar is produced if it is not properly controlled. Steam pyrolysis and hydrothermal carbonization are promising approaches for the sustainable production of biochar with reduced environmental impact; nitrogen oxides and sulfur oxides dissolve in water thereby reducing air pollution, and no pre-drying is required, resulting in reduced energy consumption and greenhouse gas emission (Sun et al. 2022). These methods are being explored as potential alternatives to traditional pyrolysis and combustion techniques for the conversion of biomass into valuable carbon-rich products. This leads to the partial de-volatilization of a portion of the material and the creation of new pores on the surface, and also results in the formation of several new functional groups namely, carboxylic, carbonyl, ether, and amine groups (Tang et al. 2018b). A temperature of 800 °C is applied to biochar in the presence of hydrogen gas to increase its crystalline nature and the formation of the carbon-hydrogen (C–H) bond and it is called "heat-treated" biochar because heat is used as an activator. Table 8 summarises the different activation agents used to enhance the characteristics of biochar.

5.2 Chemical activation

Nitric acid, NaOH, KOH, H_2SO_4, HCl, K_2SO_4, and $ZnCl_2$ are a few chemicals that act as chemical activators combined with heat (Liang et al. 2019). Dehydration and oxidation are the first two steps in the chemical activation process that result in the formation of micropores (Tang et al. 2018b). Sometimes the biochar's carbon and volatile components are removed by the chemical activating agents, which cause tar to form. Compared to physical methods, chemical activation techniques have several advantages, namely lower pyrolysis temperatures, a high biochar yield, an increased specific surface area, increased micropore formation, increased porosity, and improved removal efficiency. A 1:10 ratio of acid to biochar is added for acid activation. Phosphoric acid is an extensively used acid-activating substance. The formation of phosphate and polyphosphate bridges by phosphoric acid will increase the pollutants' ability to bind to them. The most extensively utilized alkaline activating agents are NaOH and KOH. KOH will increase the K^+ ions on the biochar's surface, which might lead to increased metal sorption.

6 Biochar applications

When compared to commercially available activated carbon, biochar has a much higher carbon content. Therefore, biochar is widely used in the environment and serves as an environmental management tool for several pollution control techniques (Sohi et al. 2009). Biochar has a wide application in biofuel industries, soil

Table 8 Activation of biochar using different agents and enhanced properties (Sakhiya et al. 2020)

S. No.	Feedstock	Activation agent	Temperature (°C)	Pore diameter (nm)	BET Surface ($m^2\ g^{-1}$)	Pore Volume ($cm^3\ g^{-1}$)	References
1	Burcucumber	Steam	300	0.541	1.22	0.003	Rajapaksha et al. (2015)
2	Coconut	Steam	800	0.425	626.8	0.336	Kołtowski et al. (2016)
3	Coconut shell	H_3PO_4	500	–	–	0.652	Prauchner and Rodríguez-Reinoso (2012)
4	Coconut shell	CO_2	750	2.85	613	0.437	Guo et al. (2009)
5	Corn hulls	CO_2	700	–	902–977	0.328–0.335	Zhang et al. (2005)
6	Corn stover	CO_2	800	–	616–712	0.422–0.549	Zhang et al. (2005)
7	Macro algae	Steam	700	1.25	57.9	0.02	Cho et al. (2013)
8	Oak	CO_2	700	–	642–644	0.404–0.411	Zhang et al. (2004a, b)
9	Olive stones	$ZnCl_2$	500	–	750	0.31	Nakagawa et al. (2007)
10	Organic sewage sludge	H_2SO_4	650	5.21	408	0.523	Zhang et al. (2005)
11	Rice straw	KOH	700	2.18	772.3	0.422	Cha et al. (2010)
12	Sludge char	HOH	700	3.09	782.6	0.606	Cha et al. (2010)
13	Soybean oil cake	K_2CO_3	600	1.04	643.54	0.336	Tay et al. (2009)
14	Sunflower seed	$ZnCl_2$	600	2.42	249.3	0.151	Angin et al. (2013)
15	Wheat straw	Steam	800	0.975	246.2	0.158	Kołtowski et al. (2016)
16	Willow	Steam	800	0.545	840.6	0.576	Kołtowski et al. (2016)
17	Wood	Steam	600	–	389	0.161	Zhu et al. (2018)

enrichment, building industry, carbon sequestration, and improving the composting process.

6.1 Biochar for soil enrichment

In agricultural practices, biochar is regarded as "black gold". Land overuse and recent agricultural practices have altered soil properties, resulting in a slew of ecological issues. The decreased microorganisms in the soil are causing many problems in the ecosystem. The incorporation of biochar into the soil can bring about numerous positive changes, creating a more fertile, productive, and sustainable soil environment. However, it's essential to consider factors like biochar type, feedstock, application rates, and the specific needs of the soil and plants when utilizing biochar for soil improvement (Jones et al. 2010). Biochar is composed of stable, easily degradable carbon. The easily degradable biochar dissolves in the soil, increasing soil biomass, soil microorganism activity, and soil enzyme activity. These microorganisms will degrade the biochar's available carbon. This process will increase soil fertility by improving the soil's nutrient content. Additional biochar application to the soil will improve carbon dioxide capture in the soil. Biochar acts as a carbon sink since a stable carbon in the atmosphere requires 100 years for the degradation process.

Soil bulk density, porosity, water holding capacity, color, and temperature are all significant physical characteristics of the soil. Soil bulk density is very important in determining soil physical properties. The bulk density of soil must be reduced to increase nutrient release and retention. Lower soil porosity corresponds to a larger bulk density of the soil (Méndez et al. 2013). The addition of biochar will enhance the porosity of the soil because the porosity of the biochar is greater than the porosity of the soil. Several investigations have confirmed that adding biochar to soil boosts porosity by lowering the bulk density. Clayey soil is less porous in general, whereas coarse or loose sand is more porous. The more porous nature of the soil, the less the water holding capacity which affects crop yield. To overcome this disadvantage, applying biochar to lose soil diminishes the porosity of the soil and changes its structure and texture. The addition of biochar to the soil will stimulate microbial growth and enzymatic activity. Similarly, it was reported that adding biochar in various proportions ranging from 5 to 25% increased water holding capacity by 260 and 370%, respectively (Brockhoff et al. 2010). The addition of biochar will alter the color of the soil because biochar has a color similar to charcoal and it will appear black. The black color absorbs the entire wave that it receives from the sunlight and warms the soil's surface, resulting in a rise in soil temperature. The soil surface temperature will rise, promoting root formation, while the moisture in the soil will be lost on the soil's surface. This will inhibit the growth of bushes and weeds. Many investigations demonstrated that adding biochar to the soil raises the temperature by 0.5–0.8 °C (Zhang et al. 2013).

Biochar will also improve the soil's chemical properties, such as organic matter, nitrogen, carbon, and soil pH. Biochar contains a variety of micronutrients, including nitrogen, phosphorus, potassium, calcium, magnesium, and sulfur. The addition of biochar into the soil will boost micronutrient contents and plant growth and also increase the nitrogen content (Glaser et al. 2001). The microorganism will convert the nitrate nitrogen into organic nitrogen. This nitrogen will be absorbed by biochar, reducing nitrogen leaching. The biochar will reduce the loss of nitrogen content in the soil. The pH of the biochar ranged from 4 to 12, contingent on the type of feedstock. There is evidence to support that applying biochar to acidic soil raises its pH. The soil's biological activity is increased by the addition of biochar. The microbial population, specifically bacteria, fungi, and enzymatic activity, will be boosted. Many studies have confirmed that, compared to raw biochar, the application of enriched biochar significantly enhances soil fertility. Enriched biochar maintains higher levels of soil organic matter and releases more micronutrients (Kizito et al. 2019). Figure 5 depicts the application of biochar into the soil to enhance its properties.

6.2 Biochar for wastewater treatment

The increase in population and industrial activity resulted in the release of huge quantities of wastewater into the environment. Some of the most common toxic pollutants that enter the environment are dyes and heavy metals. These toxic pollutants are non-biodegradable, and even a very small quantity (1 mg L^{-1}) will harm the environment. The elimination of these pollutants can be accomplished using a variety of techniques. Coagulation, reverse osmosis, ion exchange, membrane filtration and biosorption are a few of the often-employed techniques.

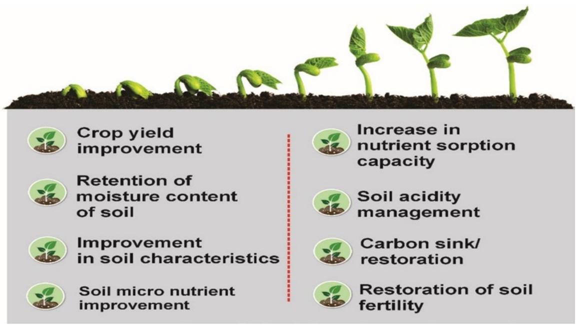


Fig. 5 Biochar application to enhance the soil properties

Of all the other treatment methods, biosorption is considered to be the most preferred water and wastewater treatment technique. The biosorption process utilizes biological materials for the sorption of pollutants and the cost for the treatment of one million liters of water is around 10 to 200 USD (Adewuyi 2020). So, the treatment cost is very low for biosorption when compared to all other treatment methods. Activated carbon, zeolite, and silicates were the most widely utilized adsorbents, but the cost to synthesize these materials is high, resulting in the exploration of new adsorbents that could have high removal efficiency with less treatment cost. The characteristics of the carbon-rich substance biochar are similar to those of activated carbon. The high carbon content, occurrence of pores, high surface area, and presence of several functional groups make biochar a promising tool in wastewater treatment (Oliveira et al. 2017). Many investigators have successfully produced biochar from several biomass wastes, and the removal efficiency is very high, making it comparable with activated carbon. The removal of the pollutants is based on adsorption mechanisms, namely electrostatic attraction, the ion exchange process, and binding in pores. Figure 6 depicts the application of biochar in wastewater treatment in different industries, while Table 9 summarizes the removal efficiency and adsorption capacity of different biochar. In summary, biochar, enriched with the aforementioned properties, serves as an effective adsorbent for pollutant removal. Furthermore, depending on the type of pollutants, engineered biochar plays a crucial role in their adsorption.

6.3 Biochar for biogas production

Anaerobic digestion (AD) is a well-known treatment unit for the degradation and conversion of volatile organic compounds into bioenergy. Methane gases are the major

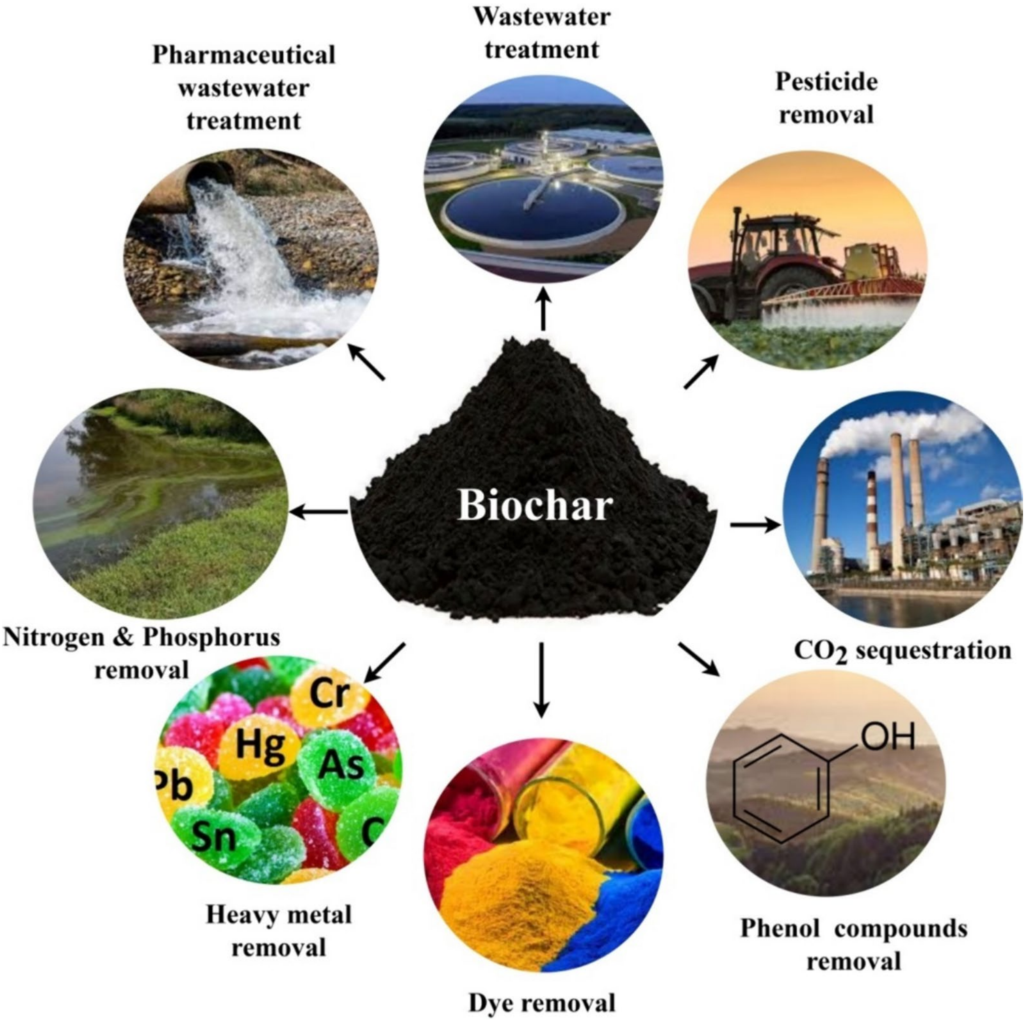


Fig. 6 Application of biochar in wastewater treatment

Table 9 Removal of pollutants using different types of biochar (Cheng et al. 2021)

S. No.	Biochar feedstock	Pyrolysis temperature	Pollutant	Adsorption capacity (mg g^{-1})	Removal efficiency (%)	References
1	Aerobic granular sludge	700	Tetracycline	93.44	–	Yan et al. (2020)
2	Alfalfa hays	300	Tetracycline	302.37	–	Jang and Kan (2019)
3	Bagasse	600	Spiramycin	–	56	Inyang et al. (2015)
4	Bagasse	600	Sulfadimethoxine	54.38	–	Yao et al. (2018)
5	Bagasse	600	Spiramycin	8.6	–	Yao et al. (2018)
6	Bagasse	800	Sulfadimethoxine	187.31	–	Zhang et al. (2020b)
7	Bamboo	500	Tetracycline	–	95.75	Wang et al. (2020b)
8	Bamboo	450	Spiramycin	–	89.6	Huang et al. (2020)
9	Bamboo	800	Nonylphenol	–	85	Dong et al. (2019)
10	Banana peel	600	Bisphenol A	–	90	Rong et al. (2019)
11	Coconut, pine nuts, and walnut shells	500	Tetracycline	94.2	–	Shan et al. (2016)
12	Coconut, pine nuts, and walnut shells	500	Carbamazepine	62.7	–	Shan et al. (2016)
13	Coffee grounds	250	Tetracycline	–	96	Nguyen et al. (2019)
14	Corn stalks	300	Bisphenol A	476.19	–	Zhao et al. (2017a)
15	Cotton straw	350	Estradiol	–	87	Wang et al. (2019)
16	Cotton straw	350	Ethinyl estradiol	–	75	Wang et al. (2019)
17	Date palm waste	600	Chlortetracycline	28.19	–	Wang et al. (2020b)
18	Date palm waste	600	Chlortetracycline	30.42	–	Ahmad et al. (2019)
19	Date palm waste	600	Chlortetracycline	45.57	–	Ahmad et al. (2019)
20	Date palm waste	600	Chlortetracycline	89.05	–	Ahmad et al. (2019)
21	Hickory chip	450	Sulfadimethoxine	–	83.3	Huang et al. (2020)
22	Litchi	650	Estrone	4.18	–	Tao et al. (2020)
23	Municipal sewage sludge	800	Tetracycline	286.913	–	Tang et al. (2018a)
24	Municipal sludge	800	Tetracycline		86	Zhou et al. (2019)
25	Pinus taeda	–	Tetracycline	274.8	–	Jang et al. (2018)
26	Poplar	300	Tetracycline	21.17	–	Huang et al. (2017)
27	Pristine hickory	600	Spiramycin	–	86	Inyang et al. (2015)
28	Reed straw	500	Sulfadimethoxine	–	81.21	Xie et al. (2019)
29	Rice	400	Nonylphenol	–	96.2	Hussain et al. (2017)
30	Rice husk	–	Tetracycline	18.53	–	Jing et al. (2014)
31	Rice husk	500	Estradiol	44.9	–	Zhang et al. (2019)
32	Rice straw	300	Tetracycline	98.33	–	Dai et al. (2020)
33	Sawdust	700	Bisphenol A	66.02	–	Jiang et al. (2019)
34	Shredded cotton stalks	350	Sulfadimethoxin	–	71	Sun et al. (2018)
35	Shredded cotton stalks	350	Sulfamethazine	–	74	Sun et al. (2018)
36	Shredded cotton stalks	350	N4-acetyl-sulfamethoxazol	–	68	Sun et al. (2018)
37	Shredded cotton stalks	350	Sulfamethazine	–	49	Sun et al. (2018)
38	Shredded cotton stalks	350	Sulfadimethoxine	–	39	Sun et al. (2018)
39	Spruce	1200	Bisphenol A	77.4	–	Baldikova et al. (2020)
40	Swine manure	700	Tetracycline	365.4	–	Chen et al. (2018)
41	Thalia dealbata	500	Sulfadimethoxine	–	86.1	Tao et al. (2019)
42	Wasted sludge	750	Tetracycline	183.01	–	Liu et al. (2019)
43	Wheat straw	700	Tetracycline	268.3	–	Li et al. (2020)
44	Yak dung	700	Tetracycline	–	77.78–91.14	Wu et al. (2019)

by-product that is produced in the AD process (Wang et al. 2020a). In the AD process, specific quantities of CO_2 and H_2S are released. The CO_2 emitted lowers the calorific value of the methane produced. Additionally, there are several other disadvantages, including very low methane yield, incomplete degradation of volatile organic compounds, and plant failures due to insufficient microorganisms and challenges in maintaining pH levels (Pan et al. 2019). So, technology development needs to be adopted for anaerobic digestion to enhance biogas production. Recently, it was proven by several researchers that the addition of biochar to the anaerobic process will enhance biogas production. Biochar addition will reduce the toxin inhibition, reduce the lag time for methanogenic bacteria, and enhance the transfer of electrons between acetogenic and methanogenic bacteria (Martínez et al. 2018). Further, the addition of biochar enhances the biogas production by 22 to 40% and diminishes the lag time by 28 to 64%. The methanogen bacteria were enhanced by 43.5%, and other microorganisms were increased by 24% (Zhao et al. 2021). Biochar application in anaerobic digestion for biogas production has several it acts as an adsorbent that could able to adsorb toxic metals, pesticides, and several other ions, biochar acts as a buffering agent, biochar also enhances the electron transfer between microorganisms, biochar increases the microbial metabolic activities and biochar also helps in the reduction of bacterial lag phase (Liu et al. 2021a). It has been reported that biochar derived from crop residues enhances methane production in thermophilic anaerobic digestion processes, while woody biochar boosts methane gas generation in mesophilic anaerobic digestion (Hoang Anh et al. 2022).

6.4 Biochar in the construction industry

Figure 7 depicts the use of biochar in the construction industry. In recent years, the pollution created by cement industries has been very high and has been a major environmental challenge (Abdoulmoumine et al. 2015). As a result, many researchers are focusing on alternative materials for cement replacement. The application of biochar in the construction industry has increased recently due to its properties. Biochar's high carbon capture capacity and low thermal conductivity act as insulation and can be used to adsorb noise (Lee et al. 2019). The main properties of the cement are quick setting time, workability, and high strength (Khamlue et al. 2019). The demand for cement has risen dramatically in recent

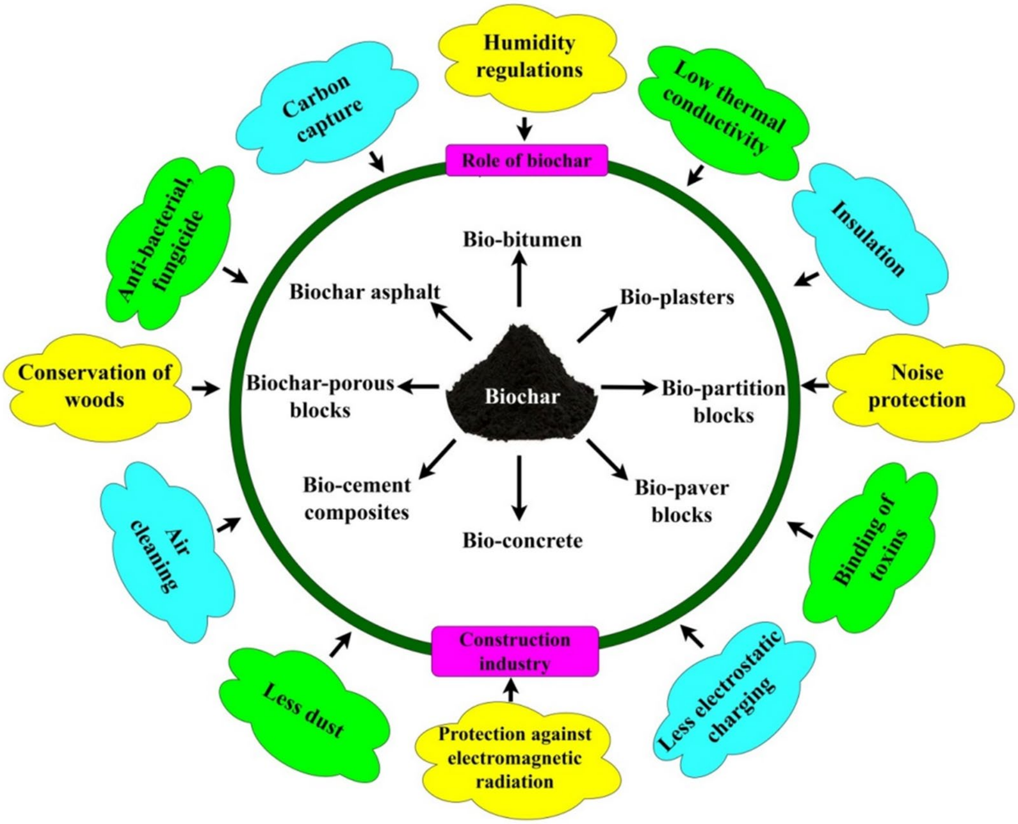


Fig. 7 Biochar application in the construction industry to enhance the properties of conventional materials

years as industrial activity has increased. Ordinary Portland cement is prepared from naturally available materials, namely clay and limestone, and industrial slag and fly ash are also used in cement production. The cement production process operates at a temperature of 1400 °C and is considered one of the energy-intensive processes. The release of CO_2 is very high in the cement production process, and CO_2 emissions from the construction sector are the major contributors to greenhouse gas emissions (4 to 7%). It is also estimated that nearly 900 kg of CO_2 is emitted for every tonne of cement (Roberts et al. 2010). To overcome this challenge, many materials, namely fly ash, slag, rice husk ash, palm oil fuel ash, and biochar, are used as partial replacements. Many researchers have successfully applied 1 to 3% of biochar as a replacement for cement. Biochar is currently used in biochar-modified red clay composites, inorganic clay composites, asphalt mixtures, and biochar-based geopolymers. Biochar can also be used as a low-carbon filler material in the manufacturing of cement, which could result in a reduction of carbon dioxide.

6.5 Biochar as a catalyst for the biofuel industry

Biochar produced through Thermochemical Conversion Technology (TCCT) can be used as a catalyst in the transesterification and fermentation processes (Alam et al. 2012). Biofuel is produced via chemical, biological, and thermochemical processes. Transesterification is a chemical method that is used for anaerobic digestion and dark fermentation. It is based on a biochemical method and a thermochemical method that includes torrefaction, hydrothermal carbonization, and gasification (Hossain et al. 2019). A catalyst is an accelerating agent that is added to biofuel production to enhance the rate of reaction and thus the biofuel yield. Catalysts are broadly classified as homogeneous or heterogeneous. Due to their ease of separation during the synthesis of biodiesel, heterogeneous catalysts are typically favored over homogeneous catalysts (Ribeiro et al. 2011). Carbon-rich biochar and the existence of aromatic hydrocarbons are very important in biofuel production because they act as heterogeneous catalysts. Lipase is an enzyme that is used to convert lipids into biodiesel. Recently, biochar has been utilized as a catalyst to convert lipids into biodiesel. Other reasons why biochar is used as a catalyst are its low cost, presence of multiple functional groups, increased surface area, stable structure, thermal and mechanical stability, and environmentally friendly nature (Yu et al. 2010).

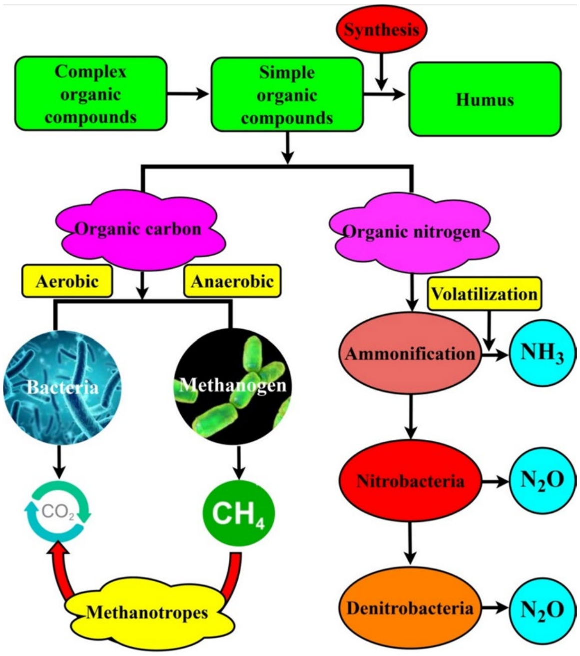


Fig. 8 Compositing process and release of greenhouse gases (GHGs) (Yin et al. 2021)

6.6 Role of biochar in composting

One of the most important biodegradation methods for solid waste is composting (Fig. 8). The compost has a high organic content and will boost crop yield (Byers 2021). Composting's main disadvantage is the release of secondary pollutants such as methane gas and other odors. This has become a major environmental concern in recent years. It has been reported that during the composting process, approximately 0.6 to 10 g kg^{-1} of nitrous oxide and methane gases are liberated. Furthermore, in some cases, due to oxygen depletion during the composting process, aerobic conditions are converted to anaerobic conditions (Akdeniz 2019). The release of H_2S, CO_2, CH_4, and N_2O will be increased during the anaerobic composting process. When volatile organic compounds decompose and react with the sun's ultraviolet rays, ozone is formed. This will increase the amount of ground-level ozone, which is a significant source of air pollution. The addition of biochar to compost will improve decomposition and reduce GHG emissions (Agyarko-Mintah et al. 2017). When biochar was added to the compost, the operating conditions drastically changed. The compost's pH was raised from 6.5 to 7.5, the moisture content was increased from 50 to 60%, the C/N ratio was raised from 20 to 25:1, and the biochar dose was raised from 1 to 20%. Increased oxygen availability, microbial growth, and humification were all influenced by these operating conditions. Further application of biochar to the composting process will improve thermophilic degradation, resulting in a faster decomposition process, a lower pH value, and less ammonia gas emission. Approximately 98% of ammonia gas emissions will be reduced, 80% of methane gas emissions will be reduced, and 50% of volatile organic compounds (VOCs) will be reduced. Table 10 summarizes the impact of biochar in the composting process and the emission of GHGs.

7 An economic barrier to biochar

Financial constraint is considered one of the major barriers to biochar production for commercial enterprises and land managers (Li et al. 2023). Biochar production costs include capital and operating expenditures. The feedstock quality and availability decide the overall production cost of biochar in different regions. The capital cost includes infrastructure, equipment, and vehicles used for the transportation of the feedstocks, and the operating cost includes maintenance, repair works, manpower, and other taxes related to biochar production (Bergman et al. 2022). Globally, the current biochar production technique suggests that the cost of biochar production is very high and several new technologies need to be adopted to reduce the cost of biochar production. The major drawback is the cost associated with pyrolysis plants is very high and the incentives provided by the government for reaching carbon neutrality are comparatively much less. Table 11 summarizes the cost of biochar production in different countries.

Table 10 Impact of biochar in composting process and emission of GHGs (Yin et al. 2021)

S. No.	Composting material	Biochar feedstock	Green house gas emission control (%)				References
			CO_2	CH_4	NH_3	N_2O	
1	Chicken manure and barley straw	Hard wood and softwood (4:1)	21.5–22.9	77.9–83.6	35.3–43	16.1–35.3	Chowdhury et al. (2014)
2	Chicken manure and sawdust	Straw	–	–	12.4	–	Zhang et al. (2020a)
3	Chicken manure and wheat straw	Hen Manure	–	20.5–61.5	19.2–48.1	4.7–15.1	Chen et al. (2020)
4	Green waste and municipal solid waste	Holm oak	52.9	95.1	–	14.2	Vandecasteele et al. (2016)
5	Layer manure and sawdust	Corn stalk	–	15.5–26.1	9.2–24.8	–	Chen et al. (2017)
6	Pig manure and sawdust	Bamboo	–	54.4	12.4	36.1	Mao et al. (2019)
7	Pig manure and wheat straw	Tobacco stalk	26.1	41.7	35.9	64.9	Wang et al. (2018)
8	Poultry litter and sugarcane straw	Green waste	–	77.8–83.3	54.9–60.2	68.2–74.9	Agyarko-Mintah et al. (2017)
9	Poultry manure and wheat straw	Bamboo	5.5–72.6	12.5–72.9	19–77.4	12.4–81.6	Awasthi et al. (2020)
10	Sewage sludge and wheat straw	Wheat straw	–	92.8–95.3	58–65.2	95.1–97.3	Awasthi et al. (2017)

Table 11 Cost of biochar production from different feedstocks in different countries (Zhang et al. 2022a)

Feedstock	Country/region	Cost ($/kg)	References
Coconut Shell Biochar	India	0.55	Praveen et al. (2021)
Groundnut Shell Biochar	India	0.55	Praveen et al. (2021)
Rice Husk Derived Biochar	India	0.51	Praveen et al. (2021)
Coconut shell AC	China	1.5–3	Alhashimi and Aktas (2017)
Granular AC	China	6.4	Alhashimi and Aktas (2017)
Tree branch biochar	Kansas, USA	11	Alhashimi and Aktas (2017)
Chicken manure biochar	Korea	1.30	Nguyen and Lee (2015)
Amine-MBC	Korea	2.60	Nguyen and Lee (2015)
Virgin wood feedstock biochar	Massachusetts, USA	17.8	Alhashimi and Aktas (2017)
Chitosan AC	Thailand	15.4	Babel and Kurniawan (2004)
Commercial AC	Thailand	21	Goyal et al. (2008)
Oiltea camellia shell biochar	USA	0.67	Cai et al. (2021)
Water oak wood biochar	USA	0.77	Li and Chen (2018)
Coconut shell biochar	USA	0.80	Alhashimi and Aktas (2017)
Switchgrass biochar	USA	5.49	Li and Chen (2018)
Sludge derived biochar	USA	0.7	Cheng et al. (2020)

8 Challenges

Despite several advantages of biochar, globally, still there are many challenges in biochar production and its application.

a. Feedstock selection and availability: Biochar quality and quantity depend on the type of feedstock used in the thermochemical conversion process. For instance, contaminated feedstock affects the biochar quality and it has a huge impact on soil remediation and water/wastewater treatment. Feedstock shape and size are other important factors that will result in pre-treatment and increase the cost of energy during the production process. For biochar to be produced, biomass feedstock must be consistently available. It is crucial to guarantee a steady and sustainable supply of feedstock. Initiatives like encouraging the cultivation of energy-focused crops, supporting responsible land management techniques, and making use of forestry and agricultural residues can all help address this.
b. Biochar production inconsistency: Several factors, including feedstocks, production techniques, pyrolysis temperature, particle size and shape, operating conditions, and heating rate, contribute to variability in biochar production. For example, an increase in pyrolysis temperature leads to a reduction in the content of volatile matter, hydrogen, and oxygen. Variations in feedstocks will result in variations in the pH of the biochar produced and physic chemical properties of the biochar. Improper application of this biochar to any environmental applications will result in a change in pH, and surface area, and these result in some chemical reactions leading to the production of some secondary pollutants.
c. Technological barriers: there are several technological barriers to scaling biochar into large-scale production. Some of the major barriers are feedstock availability and quality, production cost, infrastructure and technology, quality standards and certification, market development and demand, and environmental and social considerations. Scaling up biochar production to a large scale is expensive and cost-effective production methods need to be implemented in order to overcome this issue. New novel methods for biochar production need to be developed in the future to have a sustainable cost-effective production method.

In addition to the above, government incentives and subsidies will pave the way for large-scale biochar production. For biochar to be used in a variety of industries, its quality must be consistently maintained. Setting up certification procedures and quality standards can reassure consumers and promote market expansion. To create and execute such standards, cooperation between researchers, policymakers, and industry stakeholders is required. The market for biochar needs to be expanded to grow. Educating people about the advantages of biochar in a variety of fields, such as horticulture, environmental remediation, and agriculture, can help create demand. Governments can encourage the growth of the market by implementing biochar-promoting policies, such as grants, incentives, and procurement plans. Potential effects on the environment and society should be taken into account when producing and using biochar on a large scale. Implementing biochar sustainably requires evaluating life cycle effects, such as greenhouse gas emissions, water use, and changes in land use. It is essential to interact with stakeholders and local communities to resolve issues and guarantee that benefits are distributed fairly.

9 Future perspectives

In the realm of renewable resources, biochar stands out as a promising solution to various environmental challenges. To pave the way for its commercial applications, a thorough techno-economic analysis and life cycle assessment should be undertaken to gauge its environmental impact and sustainability across different sectors. Further research is essential to optimize biochar activation methods for specific applications and to elucidate its interaction with soil microbial populations. The mechanism behind biochar's efficacy in removing toxic contaminants remains unclear, requiring more exploration, especially in the context of electrochemical conversion and its potential use as supercapacitors. Enforcing stringent regulations on biochar quality and safety is crucial, necessitating a detailed protocol for raw material selection and production methods. Innovative technologies must be harnessed to advance scientific understanding of biochar's reactions with different materials, supporting its performance development in various sectors. Comprehensive studies on the impact of production processes on biochar characteristics are vital, especially considering variations in the types of biochar used for energy, agriculture, and water treatment. Biochar also exhibits great potential for synergistic integration with other sustainable energy technologies. When combined with renewable energy systems, such as biomass or solar power, biochar production can become an integral part of a circular bio-economy. The waste generated from renewable energy processes can be utilized as feedstock for biochar production, creating a closed-loop system that minimizes environmental impact. Ultimately, circular bio-economy practices hold the key to unlocking sustainable solutions across diverse sectors.

10 Conclusion

Waste-to-energy conversion will propel environmentally sustainable development. The various feedstock and production routes of biochar, such as pyrolysis, gasification, torrefaction, and hydrothermal carbonization, were discussed and summarised in this article. Biochar's physicochemical properties are crucial for mitigation strategies. The environmental application of biochar was also summarised. The use of biochar in wastewater treatment is being investigated to the greatest extent possible. Biochar was utilized to eliminate toxins like heavy metals, dyes, cosmetic pollutants, and merging pollutants. The construction industry, composting processes, biofuel industry, and carbon capture technology are all interested in biochar applications. Future efforts should focus on optimizing production processes, tailoring biochar properties, and exploring diverse environmental applications. Public awareness, policy support, and collaboration between research, industry, and policymakers are crucial for maximizing the environmental benefits of biochar. To support the commercialization of biochar for large-scale uses, a thorough evaluation of the advantages and disadvantages of biochar for various environmental applications in terms of technical, environmental, economic, and social issues is necessary. Further research should focus on the environmental sustainability of biochar since the rate of mineralization of carbon in biochar depends on several factors and this issue can be addressed by conducting several field studies and exploring the potential of biochar.

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